ELECTRONIC FUNDAMENTALS

THEORY LESSON 34

VOLUME AND TONE CONTROL CIRCUITS

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34-2. Simple Tone Controls Based on Resistor-Capacitor Networks

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A SERVICE OF RADIO CORPORATION OF AMERICA

HOME STUDY SCHOOL

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Theory Lesson 34

INTRODUCTION

A sound reproducing system in which the performance is so accurate that the reproduced sounds cannot be distinguished from the original can be considered to be an ideal system for most listeners, but not for everyone. Some persons like to hear music with the treble muted. Some like to hear the bass exaggerated. Others, particularly those who are hard-of-hearing like the bass attenuated and the treble emphasized.

With these and other considerations in mind, amplifiers are designed so that the *relative* levels at which bass, middle, and treble regions of the audio range are reproduced can be varied by the user. Since bass, middle, and treble portions of the audio range are simply different frequencies in the audio range, we can use filter circuits to regulate the amount of these frequencies passed by the audio amplifier. In general, these filter circuits, called *tone controls,* control the *relative* volume at which the three portions of the range are reproduced. *Volume controls* determine the over-all, or combined, volume. Both over-all loudness and relative loudness can be varied simultaneously by means of specialized volume controls that incorporate tone controls; these combined controls are called *loudness* controls.

A loudness control changes the gain of the amplifier. Instead of being linear, the gain of the amplifier becomes nonlinear. Let's compare a linear gain with a nonlinear gain by means of graphs. In Fig. 34-1*a,* the characteristic representing relative gain versus frequency is straight. All signal frequencies are given the same amplification.

In Fig. 34-1*b,* we have plotted the gain characteristic of an amplifier fitted with tone controls, set to increase the gain for the bass, relative to the middle and reduce the gain for the treble relative to the middle. In the bass region the lowest frequency is amplified the most. In the middle region, all frequencies are amplified equally. In the treble region, the higher frequencies received less and less amplification with the highest frequency receiving least of all.

If the situation were reversed, and the controls were reset to attenuate the bass and increase the treble, the curve would be as shown at Fig. 34-1*c.*

Audio curves of the type shown in Fig. 34-1 can be used to describe the frequency response of microphones, loudspeakers, pickups, phonograph records, magnetic tapes, movie sound tracks, output transfor-

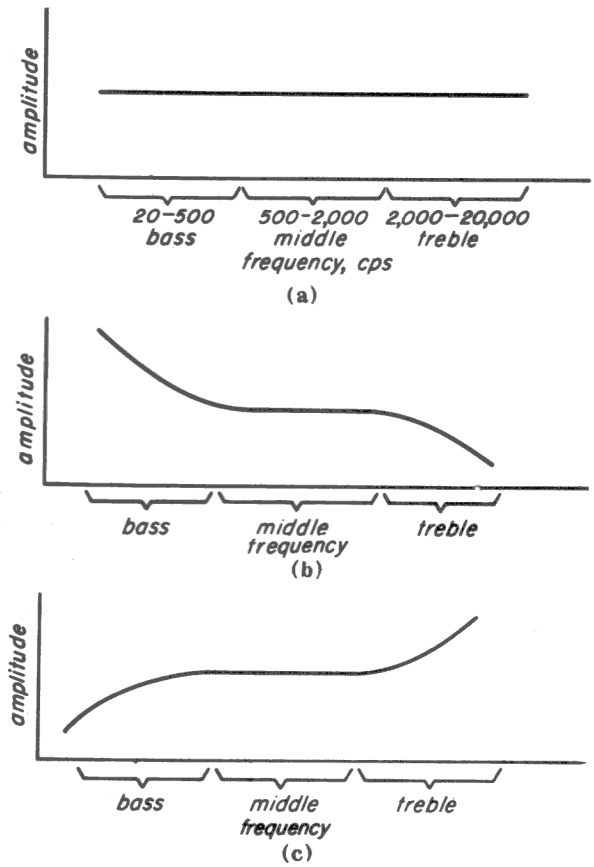


Fig. 34-1

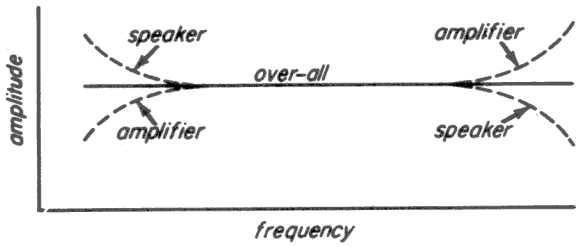


Fig. 34-2

mers, and many other audio units. They are especially helpful when you are assembling and designing *systems*. Examining the curves lets you know which units can be used in combination to get a certain kind of performance. For example, suppose you want an amplifier-loudspeaker system whose over-all response is approximately flat. But the amplifier you have (without tone controls) has a response like the one described in Fig. 34-1*c*. You have a number of loudspeakers from which to choose. By choosing the proper loudspeaker, you can cause the response of the *system* to have uniform response. If you choose a loudspeaker whose curve closely approximates the curve in Fig. 34-1*b*, the over-all curve of the system will be approximately uniform or flat. You can see this by means of the graph in Fig. 34-2. The two curves are superimposed. The resultant is a straight line (a flat characteristic). The poor treble response of the speaker may be offset by the excessive treble response of the amplifier. The excessive bass response of the speaker may be offset by the poor bass response of the amplifier. The over-all system will sound as though each of the units, amplifier and speaker, had a flat response.

However, even though it is possible to achieve a flat response, either by using a combination of components or by manipulating tone controls, it is not always desirable to have a flat response. You might even, as in the case of high-fidelity amplifiers, whose published curves are shown flat over a very wide range, start out with a flat response and vary it with tone controls. This might at first seem to be contradictory. If the purpose of the amplifier is to reproduce the original sound with the utmost fidelity, why should it include circuits that alter the relative level of the various parts of the audio range. Why should it ever have any curve except a flat one? The answer is fourfold:

1. The amplifier alone cannot reproduce sound; it must be considered together with the input device (microphone, pickup, or detector circuit) that supplies the audio signal, and the reproducing device (loudspeaker) which converts the electrical waves into sound waves. It is not easy to alter the microphone or speaker curves so as to make the system flat, but it is easy to alter the amplifier's curve in whatever direction will help to compensate for the lack of flatness in the other curves. If the *system* can be made flat by making the amplifier *not* flat, the result is still fidelity of reproduction.

2. Absolutely faithful reproduction is not always the most satisfying reproduction. Some persons enjoy bass more when it is disproportionately loud. A tone control affording bass boost is gratifying to them.

3. The original sound may not be pleasingly balanced. The violins may seem screechy to sensitive listeners. A tone control that attenuates the treble can reduce their shrillness to a less piercing level. The reproduction may be less faithful, but more pleasing.

4. The relative level of bass, middle, and treble seems to change if the total volume is changed by resetting the volume control, even though the volume control is not in a tone-controlling circuit. This effect is due to a peculiarity of the ear. In order to restore the same *apparent* tonal balance, the tone controls now have to be reset.

High-fidelity amplifiers are often designed so that when the tone controls are set near their midposition, the response of the amplifier is reasonably flat. Thus the user has leeway either side of center to turn the controls for boost or attenuation of either bass or treble.

34-1. VOLUME CONTROL AS A VARIABLE VOLTAGE DIVIDER

A volume control does not change the gain of an amplifier. It merely changes the amount of the available audio signal fed to the amplifier. Consider Fig. 34-3*a*, which shows a two-stage amplifier. The compon-

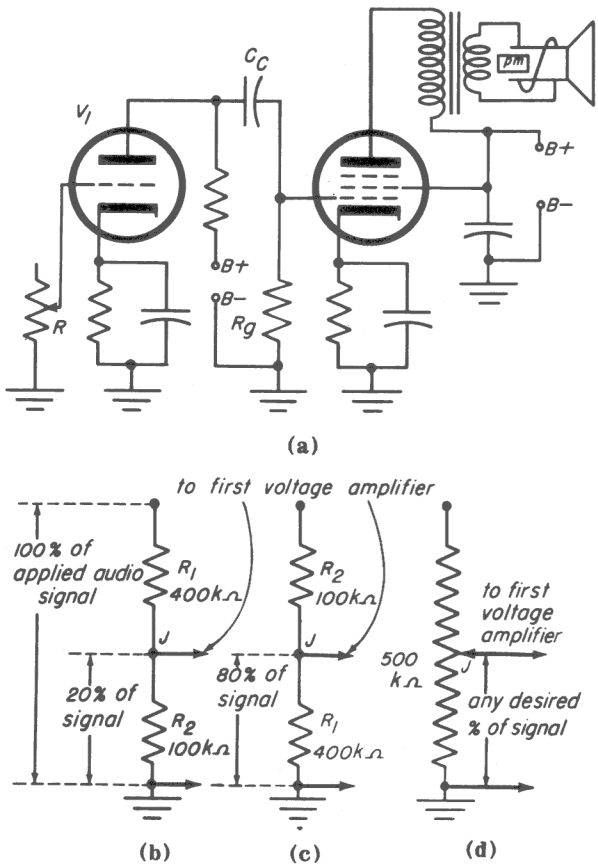


Fig. 34-3

ent labeled R is a potentiometer that serves as a volume control. Let us study the volume control in greater detail. An a-f signal is applied to the control grid and ground of V_1. Tube V_1 amplifies the signal and its output voltage appears between plate and ground of V_1. This amplified voltage is applied to the grid resistor R_g through the coupling capacitor C_c.

Let's replace the potentiometer in *a* with a voltage divider, as in *b*. The voltage divider has a total resistance of 500 k-ohms, across which an a-f voltage is applied.

The a-f voltage is tapped off at point *J*, the junction of the two resistors. Only twenty percent of the total resistance is between point *J* and ground. Therefore, only twenty percent of the applied signal is developed across R_2. If this twenty percent of signal is applied to the input of an audio amplifier, the amplifier will have less to amplify than it would if the full signal were applied. The output of the amplifier will not be as great as it would if the full signal were applied.

If we reverse the position of the resistors, as shown in Fig. 34-3*c*, putting R_1 at at the bottom of the divider and R_2 at the top, eighty percent of the total resistance is between *J* and ground. Therefore, eighty percent of the input signal is developed between *J* and ground. If this eighty percent of signal is applied to the amplifier's input, the output of the amplifier will be greater than when only twenty percent of full signal is applied. In brief, by varying the percentage of resistance between tap-off point *J* and ground, we can vary the output of the amplifier.

If we replace the voltage divider made of two resistors with another voltage divider – a volume control – made of only one 500 k-ohm resistor (see Fig. 34-3*d*), but having a sliding tap-off point, we will have the equivalent of the two resistors, except that we can have any percentage of the total resistance we choose between point *J* and ground. That is, we can apply any fraction of the full signal to the amplifier's input. We can vary the output of the amplifier from zero to the maximum that the full signal will produce. All the while, the amplifier will be operating at constant gain. But this constant gain will be acting on more signal or less signal, according to the setting of the volume control.

Figure 34-4 shows graphically what happens when the volume control is turned from a high volume setting to a low volume setting on an amplifier with a flat response. The response represented by the upper straight line falls to a lower position on the graph, shown by the lower straight line. Since the amplifier is flat, the line remains straight, indicating that although signals of all frequencies are now producing less out-

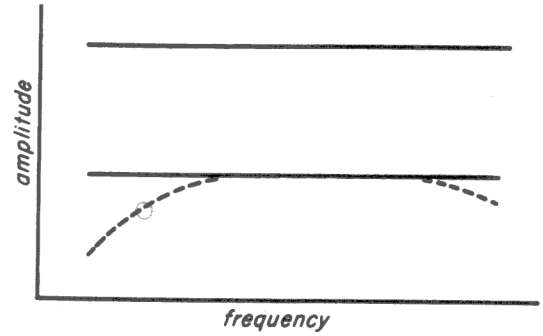


Fig. 34-4

put, they all produce the same percentage ouput relative to each other, as before. However due to nonlinear sensitivity of the ear, they do not *sound* as though they were producing the same relative percentages as before. The bass sounds much weaker, relative to the middle, than before. The treble sounds slightly weaker, relative to the middle, than before. The apparent characteristic is that of the dashed line.

In order to make the output of the amplifier *sound* flat, the tone controls must be reset to boost the bass considerably and to boost the treble slightly. The tone controls must compensate for the increasing insensitivity of the ear to the bass and treble tones at low volumes.

If, after the tone controls have been set to restore apparent flatness of the characteristic, the volume control is turned back to its original loud setting, the bass and treble will sound overemphasized. Then the tone controls will have to be reset. (Volume controls which automatically offset this apparent tonal change are discussed later in this lesson.)

Taper of Audio Volume Controls. Besides having a varying sensitivity to different frequencies at different levels, the ear also has varying sensitivity for any one frequency at different levels. If, for instance, a 1,000-cps tone is generated at a level so faint that the ear can just hear it and is then increased by a tiny amount, the ear can notice the increase. If the same tone is produced at a high level and then increased by the same amount of audio power as before, the ear cannot tell that the increase has occurred; it may be necessary to use an increase ten or twenty times as great before the ear can tell that the level has been raised. The ear may be said to have tapering sensitivity, with very poor awareness of volume changes when volume is at a high level.

In order that volume may *seem* to our ears to increase uniformly, it must actually increase at a highly nonuniform rate as we turn up the volume control. This calls for a nonlinear distribution of resistance in the resistance track. When the slider is near the high-volume end of the control, a small amount of shaft rotation will produce a much larger change in resistance than the same amount of rotation will produce when the slider is near the low-volume or ground end of the control. Such a distribution of resistance, or taper, is called essentially, *logarithmic taper,* or *audio taper,* because it is matched to the tapering sensitivity of the average ear.

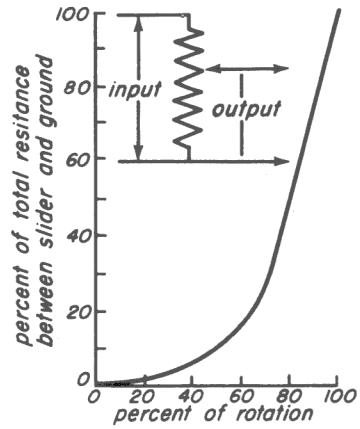


Fig. 34-5

The graph in Fig. 34-5 shows an audio taper. As shown, uniform changes in shaft rotation do not produce uniform change of resistance between the grounded end of the control and the slider. During the first fifty percent of rotation, the change in resistance is small. Only about ten percent of the total resistance is traversed. Controls used for purposes other than the regulation of volume usually have tapers suited to their functions.

Center-Grounded Volume Controls. These controls have a tap at the center of their resistance track. The tap is grounded as shown in Fig. 34-6. Two different audio signals may be applied to the control, at opposite ends, and the desired one picked off by the slider and applied to the input of the audio amplifier.

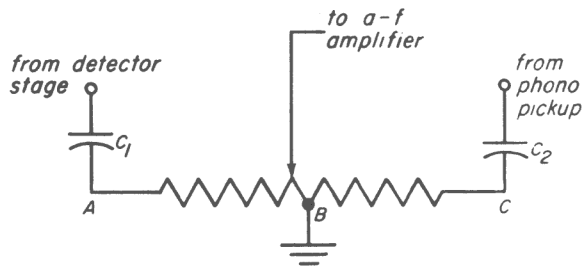
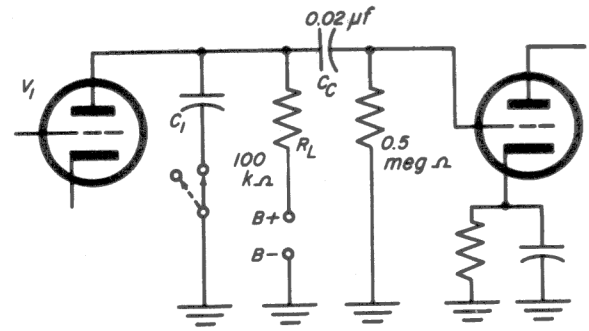


Fig. 34-6

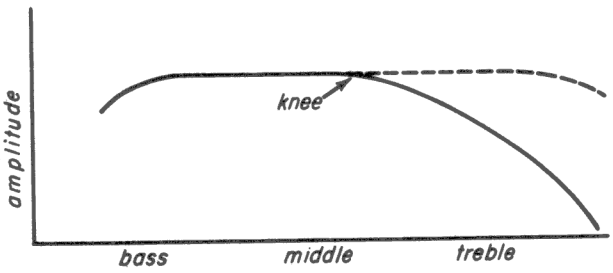
Controls of this type are occasionally used in radio-phonograph combinations. As shown in the figure, the signal from the detector stage of a radio tuner is applied between points *A* and *B*. When the slider is anywhere between *A* and *B*, the detector output is heard from the audio amplifier and speaker. The nearer the slider is to *A*, the louder is the output. When the slider is anywhere between *B* and *C*, and the phonograph is in operation, the output from the pickup is heard from the amplifier and speaker. The nearer the slider is to *C*, the louder is the recorded sound. The control normally has two audio tapers, one between *A* and *B*, the other between *B* and *C*.

34-2. SIMPLE TONE CONTROLS BASED ON RESISTOR–CAPACITOR NETWORKS

The simplest tone control is a fixed treble-cut capacitor C_1, which may be switched into or out of the circuit, as shown in Fig. 34-7*a*. It is, in effect, shunted across the plate-load resistor of an audio voltage amplifier. The impedance between B+ and B– (the power supply) in the figure is practically zero ohms for audio frequencies, due to the large power-supply filter capacitors. Thus, C_1 is shunted in effect across R_L. The effect of C_1 upon the output signals of V_1 is shown at *b*. The dashed line is the characteristic with the switch open and the capacitor not in the circuit. The solid line is the characteristic with the switch closed and the capacitor in the circuit. The point at which the solid line begins to slope rapidly downward to the right is called the knee of the curve.



(a)



(b)

Fig. 34-7

The plate-load impedance of an amplifier is one of the factors that determine stage gain. In general, the higher the plate-load impedance, the higher the gain. If the plate load is simply a resistor, the gain will be fairly uniform over the a-f range. But when a capacitor, such as C_1, is shunted across the plate-load resistor, the impedance of the plate load will vary with frequency. Since capacitive reactance decreases with an increase in frequency, the impedance of the combination, C_1 and R_L, also decreases with an increase in frequency. The capacitor C_1 can be chosen with such a value (for example, 0.005-μf) that the plate-load impedance will be lowered greatly at the upper treble frequencies, but only slightly lowered at the middle frequencies, and negligibly lowered at bass frequencies; gain will be greatly reduced at treble frequencies, but hardly changed at all over the rest of the a-f range.

The downward slope of the left end of the curve, indicating loss of bass, is not due to C_1, but to the coupling capacitor C_c, and will be discussed later.

Step-Type Tone Control. Figure 34-8*a* shows a more versatile and satisfactory arrangement than that in Fig. 34-7. A multiposition switch and several capacitors of different values (such as 0.01μf, 0.005μf, and 0.001μf) are employed as illustrated. Position 4 of the switch is not connected to any capacitor. In this position of the switch the load is as close as possible to being purely resistive. Only the normal stray capacitances of wiring and the internal capacitances of the tubes causes attenuation. Because of the very low value of these capacitances signal frequencies of 10 kc and higher are attenuated. It is because of these capacitances that all a-f amplifiers have an upper frequency limit.

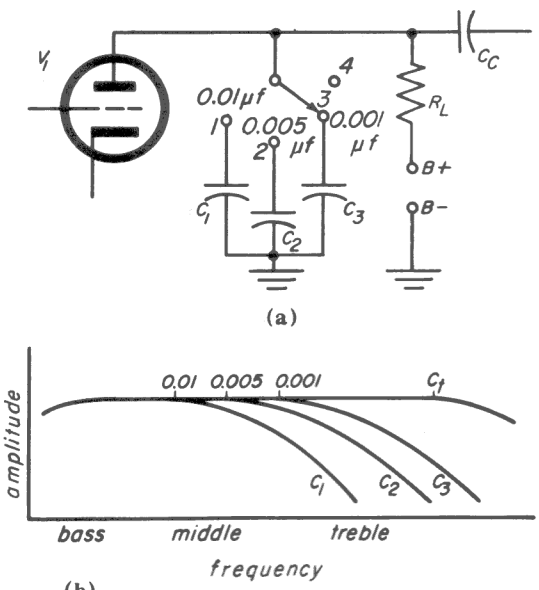


Fig. 34-8

As different capacitors are switched into action, the effect upon the output signals is the same as described in the previous example. The knee of the curve occurs at a lower frequency for larger capacitances. Fig. 34-8*b* shows four different characteristics due to the different amounts of shunting. The curve marked C_t indicates the knee due to stray capacitances and tube capacitances combined.

This system has been widely used because it affords a choice of characteristics to suit a variety of tastes or a variety of program material. Manufacturers occasionally label the different positions of the control with descriptive names, rather than position numbers. Thus position 1 might be labeled *Muted or Bass* (with treble heavily cut, bass sounds more prominent); position 2 might be labeled *Mello*; position 3, *Normal* or *Voice;* and position 4 *Brilliant.* Other terms, such as *Alto* and *Soprano* are used occasionally. They simply indicate different degrees of treble cut.

Simple Variable Treble-Cut Control. A variable characteristic can be achieved with a single shunt capacitor if it is connected in series with a variable resistor (potentiometer), as illustrated in Fig. 34-9*a*. Capaci- C_1 is chosen to have a low impedance at about 2,000 cps. A value such as 0.006μf or 0.01μf is frequently used. The potentiometer

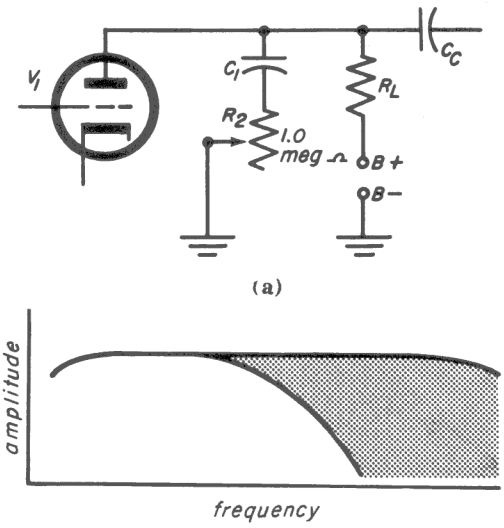


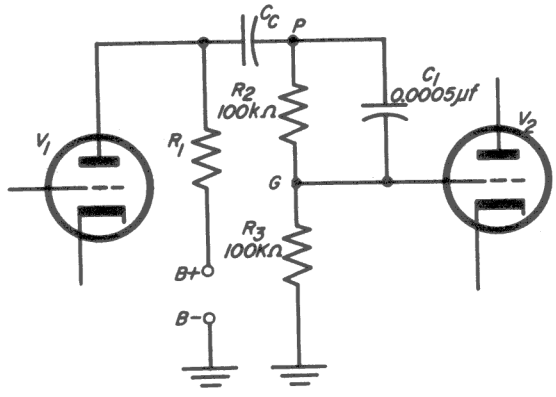
Fig. 34-9

should have a resistance of 1 megohm. The reactance of the capacitor is in series with the resistance of the potentiomenter, and the total resulting impedance is shunted across the plate-load resistor.

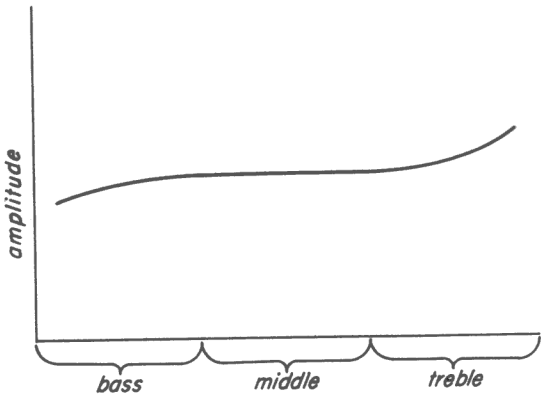
By increasing the resistor, the total shunt impedance can be made very high. Therefore, the plate-load impedance will be close to the value of R_L. In this case, no appreciable attenuation of treble will occur; or, by turning the potentiometer to zero ohms, the plate-load impedance at treble frequencies will become low—equal to the capacitive reactance. In this case, attenuation of treble will occur. At in-between settings of the resistor, in-between degrees of attenuation will occur. Any number of characteristics between the two extremes, can be had. The shaded area in *b* indicates this.

Simple Treble Boost With Capacitor. The circuit shown in Fig. 34-10*a* is practical because an amplifier in which it is to be used can be designed to offer far more gain than is needed in most amplifiers. Therefore, this type of circuit, although it introduces losses, is quite common and useful. The circuit shown, which is part of an audio amplifier, introduces a loss to the entire audio range, by means of voltage-divider action, but compensates for the loss in the treble region with capacitor C_1.

The grid of V_2 is connected to the junction of R_2 and R_3, which constitutes a volt-



(a)



(b)

Fig. 34-10

age divider. Suppose C_1 is not yet in the circuit when a signal voltage is applied between point P and ground, only 50 percent of it is developed across grid resistor R_3 (which contains only half of the total resistance between point P and ground). Therefore, only 50 percent is applied to the grid of V_2. This halving of the signals will apply to all frequencies so long as the impedance of the voltage divider is purely resistive. But when C_1 is shunted across R_2, the impedance between points P and G becomes reactive and is no longer the same for all frequencies. The capacitor C_1, chosen to have a low reactance for treble frequencies, and a much higher reactance for middle and bass frequencies, is in parallel with R_2. The impedance of R_2 and C_1 in parallel, at 20,000 cps is approximately 16 k-ohms, far less than the 100 k-ohms of R_2 alone. For a signal at 20,000 cps the impedance of the voltage divider is the impedance between points P and G, 16 k-ohms, plus the impedance between point G and ground, the 100 k-ohms of R_3. Of the total 116 k-ohms, 100 k-ohms are in the grid resistor, R_3. Therefore the voltage at point G, and at the grid of V_2, is approximately 100/116 times the voltage at P, or about 86 percent of the voltage at P.

At 1,000 cps, the center of the middle range, the reactance of C_1 and R_2 in parallel is approximately 95 k-ohms, so that the signal voltage at G is approximately 100/195 times the voltage at P, or about 51 percent of the voltage at P.

At 50 cps, the reactance of C_1 is so high that it has negligible effect upon the voltage divider. The parallel combination of C_1 and R_2 has, for all practical purposes, an impedance of 100 k-ohms, at 50 cps. Therefore, only 50 percent of the 50 cps signal is applied to the grid of V_2.

The over-all effect of C_1 is such that it lets the voltage divider introduce a loss of approximately 50 percent for all frequencies except those in the treble range. For the treble range, it *changes the reactive impedance* of the upper portion of the divider so that far less loss is introduced as frequencies approach the upper limit of the a-f range. Since less loss is introduced in the treble range, the treble signals are boosted relative to the rest of the a-f range.

This ability of a capacitor to modify the action of part of an a-f voltage divider – to make it frequency selective – is of basic importance in tone-control design, and is widely used.

Treble Boost by Controlled Degeneration. Before analyzing treble boost by this method, let us first review the principle of degeneration by studying a simplified example and the actual circuit in which degeneration occurs.

In the normal voltage amplifier of Fig. 34-11*a*, voltage *between control grid and cathode* must vary in order to produce a change in plate current. Let us assume an initial condition where there is no voltage across R_g (control grid and ground) and the voltage between cathode and ground is zero. Under these conditions, the plate current will be of a certain value. If, whenever the input signal makes the grid go positive by 2 volts, with respect to ground, we could

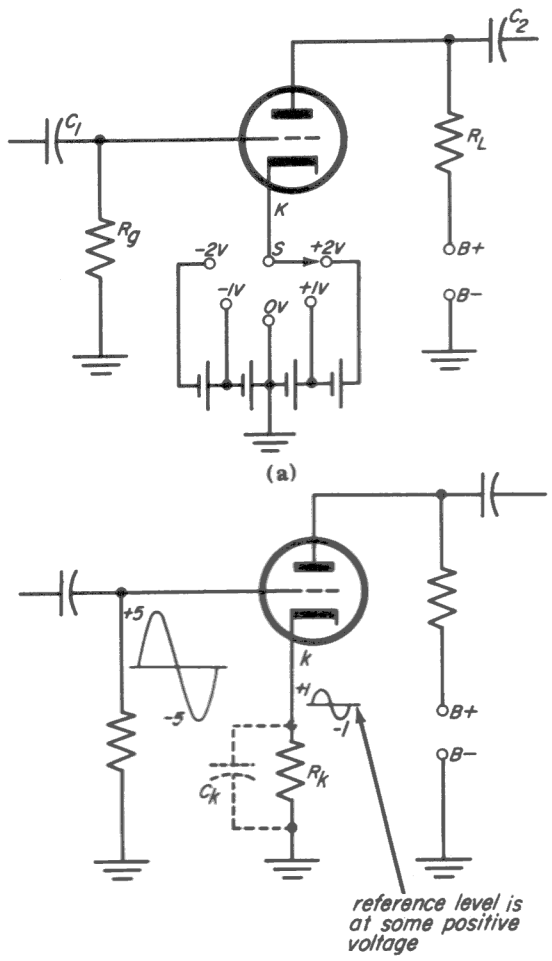


Fig. 34-11

throw switch S to the two volts position, then the cathode voltage would go positive by 2 volts with respect to ground. As a result, there still would be no difference in voltage between grid and cathode. Therefore, there would be no change of plate current, and there would be no change in the voltage across R_L. Thus, the signal on the control grid would not produce an output voltage across R_L.

But if, when the signal made the grid go 2 volts positive, we made the cathode go only 1 volt positive by throwing S_1 to the 1-volt position, there would be a net difference of voltage between grid and cathode of of +1 volt. There would be an increase in plate current, and an output voltage across R_L would result.

If the switch were kept on the zero volts position when the grid went 2 volts positive, there would be a larger change of plate current and a larger output voltage.

If, when the signal made the grid go negative, the switch were thrown to appropriate negative voltage points, relationships described above could be repeated for negative signal swings.

A similar effect can be produced by means of an unbypassed cathode resistor, as shown in Fig. 34-11*b*, which can be regarded as an automatic switch that makes the cathode go positive when the grid goes positive and less positive when the grid goes negative. For instance, when the signal applied to the grid is 5 volts positive, the cathode may become 2 volts more positive than it was when no signal was applied to the grid. When the signal on the grid is 5 volts negative, the cathode may be 2 volts less positive than it was when no signal was applied to the grid.

The cathode voltage follows the grid voltage because the plate current, in order to complete its circuit, has to flow through the cathode resistor. When the grid goes positive, increasing plate current, the greater current flowing through R_k causes a greater voltage drop across R_k, making point K go more positive. When the grid goes negative, thereby decreasing plate current, the voltage drop across R_k decreases and point K goes less positive.

This tendency of the cathode voltage to follow the grid voltage causes the *difference* voltage between them to be less than it would be if the cathode were held at a fixed voltage. The smaller the difference that the input signal produces, the smaller the output voltage. Thus the tendency of the cathode voltage to follow the grid voltage reduces the output voltage that a given signal can produce. This effect is called *degeneration.* Its essential characteristic is that the change in plate current caused by the signal produces a voltage that opposes, or subtracts from, the signal, making the signal less effective in producing output voltages.

If C_k, the capacitor shown by dashed lines, is added to the circuit, the action of the circuit will change. The value of C_k may

be so small that the parallel combination of C_k and R_k has a much lower impedance for treble frequencies, than for other frequencies. Therefore, the change in plate current due to treble input signals will produce very little change across the low impedance of the combination. There will be very little degeneration at treble frequencies, and the gain of the stage for treble frequencies will be high. Since the value of C_k is chosen so that, for middle and bass frequencies, the impedance of the combination will differ very little from the impedance due solely to the resistance of R_k, much more degeneration or reduction of gain will occur at these frequencies than occurs at treble frequencies. Treble will be boosted relative to the rest of the a-f range.

Bass Cut. At low audio frequencies, the coupling capacitor C_c of a resistance-coupled amplifier stage (Fig. 34-12*a*) is a very important factor affecting the amount of the signal actually transferred to the grid of the following tube.

Suppose C_c is 0.01μf. Its reactance at 50 cps is 318,000 ohms. In conjunction with the grid resistor, R_g, of the following stage, it forms the equivalent of a signal voltage divider (Fig. 34-12*b*). The reactance in ohms of the capacitor is almost as great as the resistance of R_g. Consequently, a large percentage of the 50 cps signal applied at P is lost in the voltage drop across the reactance of C_c. When signals of higher frequencies are applied across this network, the reactance of C_c is less. As a result, a greater portion of the voltage drop occurs across R_g. If two stages of such coupling are used, the amount of signal actually delivered to the last grid is again attenuated, relative to middle and treble, by the same large percentage. Where bass attenuation is actually desired, C_c may be even smaller than 0.01μf. On the other hand, if very good bass response is desired, C_c *can be as* large as 0.25 μf.

Simple Bass Cut Control. The circuit in Fig. 34-13 affords a moderate amount of variable bass cut. Potentiometer R_1 and capacitor C_1 constitute an impedance, Z_1, whose value varies as R_1 is varied. The network

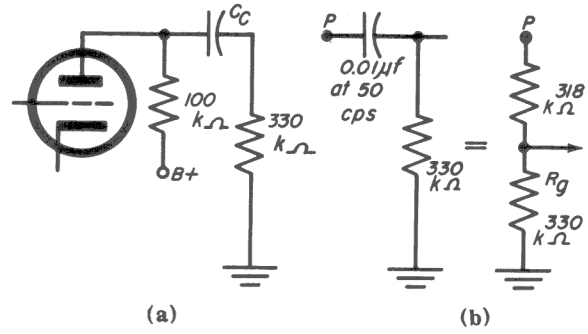


Fig. 34-12

Z_1 is in series with grid resistor R_2, with which it forms a voltage divider. The output signal is taken off at point Q, the junction of the variable impedance and R_2.

The input impedance of the voltage divider, Z_2, equals approximately $Z_1 + R_2$. The input signal is applied between point P and ground. The fraction of the input signal taken off at point Q equals R_2/Z_2 (Fig. 34-13).

Capacitor C_1 can be chosen with such a value that, for 1,000 cps and higher, the maximum impedance of Z_1, relative to the resistance of R_2, will be very low – about 1/15th of R_2 – while for a bass frequency, such as 50 cps, the maximum impedance of Z_1 will be approximately 4/5th of R_2. Thus when potentiometer R_1 is rotated from zero resistance to 500 k-ohms, Z_1 will change very little for middle and higher frequencies. For these frequencies, point Q will be high on the voltage divider, so that the output voltage at Q will be almost as great as the input voltage at P. But for a signal at 50 cps, impedance Z_1 will be almost as large as R_2, so that R_2/Z_2 will be only slightly more than 0.5 Point Q will not be high on the voltage divider for 50 cps. The output voltage will be only slightly more than one-half of the input voltage. Thus, bass will be cut when R_1 is rotated to its maximum resistance.

When R_1 *is* at zero ohms, Z_1 is zero ohms, and point Q is at the same potential as point P. Then bass is not cut. At settings between zero and maximum resistance, bass is proportionately cut.

When C_1 is chosen to be 0.0047 μf, the output voltage at 1,000 cps equals 92 per-

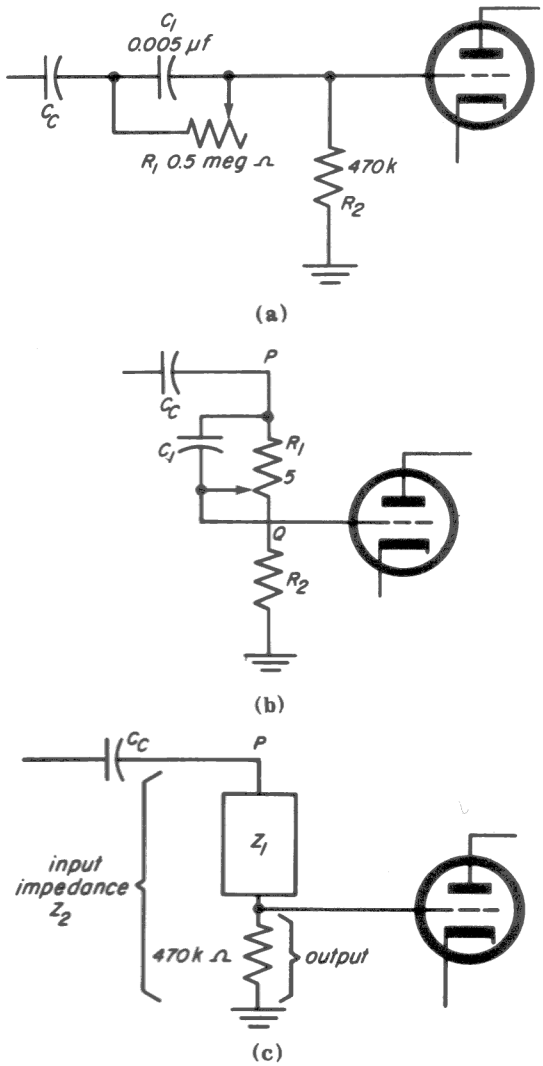


Fig. 34-13

cent of the input voltage; the output voltage at 50 cps equals 54 percent of the input voltage.

Bass Cut By Insufficient Cathode Bypassing. By allowing degeneration for *low* audio frequencies to occur in an amplifier stage, while not letting it occur for middle and treble frequencies, bass frequencies can be attenuated relative to middle and treble frequencies.

If the cathode bypass capacitor, C_k, in Fig. 34-14*a* is large enough to bypass middle and treble frequencies effectively, so that no appreciable voltage changes at those frequencies can occur across the cathode resistor, no a-c voltage can appear across R_kC_k. No appreciable degeneration occurs. Thus, the a-c impedance of R_kC_k is practi-

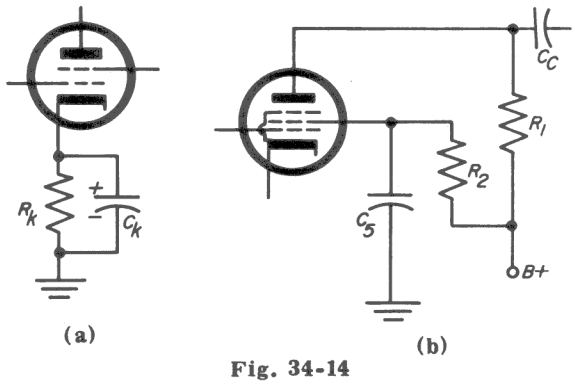


Fig. 34-14

cally zero for treble and middle frequencies. The gain of the stage for middle and treble will be maximum. But if the capacitance is not large enough to hold the cathode at ground potential for low audio frequencies, that is, if the impedance of R_k *and* C_k in parallel is relatively high for low frequencies, degeneration at these low frequencies will oppose the applied input signal and result in less gain for the bass region. Bass frequencies will be attenuated relative to middle and treble frequencies.

Bass Cut By Insufficient Screen Grid Bypassing. The plate current of a pentode varies with the screen grid voltage. If the screen grid voltage rises, the plate current increases, and vice versa.

Since the screen grid draws current and is usually supplied with B+ voltage through a dropping resistor, it is very much like a plate itself. If unbypassed, it will act as a plate. When a signal is applied to the control grid of the pentode, a reproduction of the signal will appear at the unbypassed screen grid. Just as in the case of a true plate, the reproduced signal will be 180 degrees out of phase with the signal at the control grid. The screen grid will be going negative when the control grid is going positive and vice versa. That is, when the control grid is trying to increase the actual plate current, the screen grid is trying to reduce it. With the screen grid opposing it, the control grid is much less effective in producing an output signal. As a result, the gain of the pentode is reduced.

When the screen grid is thoroughly bypassed, no signal voltage changes can occur there. Then the gain of the pentode is

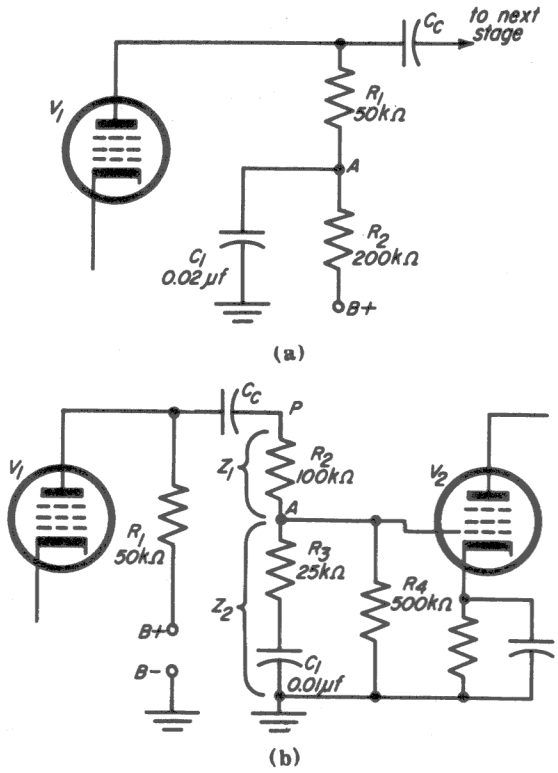


Fig. 34-15

maximum. But just as in the case of the cathode, the screen grid may be *selectively* bypassed. The capacitor C_5, in Fig. 34-14*b*, may be given such a value that it will have a relatively low impedance for middle and treble frequencies compared, to R_2, and a relatively high impedance compared to R_2, for bass frequencies. Then, only at bass frequencies will the voltage at the screen grid considerably oppose to the voltage on the control grid. Gain of the tube for bass frequencies will be reduced. Bass signals will be cut relative to middle and treble signals.

Bass Boost. The arrangement shown in Fig. 34-15 boosts bass by varying the effective resistance of the plate load of V_1. Capacitor C_1 has a low reactance at treble and middle frequencies, so that point *A* is at ground potential for them. But C_1 has a high reactance at low frequencies, so that point *A* is not effectively bypassed for them. That is, for low audio frequencies, the potential at point *A* can rise and fall at the rate at which the signal is varying. The ohmic value of C_1 can increase to such a value that R_1 plus R_2 combined constitute the plate-load resistor. Thus, for very low frequencies, the plate-load impedance approaches 250 k-ohm. Since the bass has the advantage of greater plate-load resistance, it will be amplified more than the middle and treble frequency. It will be boosted, relative to middle and treble, before reaching the next audio stage.

An alternative arrangement is shown at Fig. 34-15*b*. A signal voltage divider consisting of R_2, R_3 and C_1, is shunted across the output of V_1. Note that the grid of V_2 receives its signal from point *A* on the divider. The total impedance between point *A* and ground is the impedance of R_3 and C_1 in series. Let's call it impedance Z_2. At middle and treble frequencies, the impedance of C_1 is negligible. Therefore at middle and treble frequencies impedance Z_2 equals 25 k-ohms, about one-fifth of the total impedance (Z_1 plus Z_2) of the divider. But at low bass frequencies the impedance of C_1 is quite high (approximately 318,000 ohms at 50 cps). Thus, at 50 cps impedance Z_2 equals approximately 343,000 ohms, or roughly three-fourths of the total impedance between Point *P* and ground.

If a middle or treble signal of 1 volt amplitude is applied to point *P*, only 0.2 volts is applied to the grid of V_2. But if a 50-cps signal of 1-volt amplitude is applied to point *P*, 0.75 volt is applied to the grid of V_2. Thus, the effect of the reactive voltage divider is to boost the bass relative to the middle and treble. Resistor R_4 provides a d-c path from grid to ground. Since it is large (500 k-ohm), it has very little shunting effect on R_3 and C_1. It does not interfere appreciably with their voltage divider action.

Variable Bass Boost. A minor change in the circuit just discussed enables the degree of bass boost to be altered by adjusting a variable resistor, as shown in Fig. 34-16.

Variable resistor R_5 is connected in parallel with C_1. For any given low frequency, such as 50 cps, it limits the effective impedance R_5C_1. When R_5 is set to zero ohms, C_1 is shorted out and has no boost effect. The voltage divider then attenuates all frequencies equally. When R_5 is set to 1 megohm, R_5C_1 has about three-fourths as much effective impedance as it

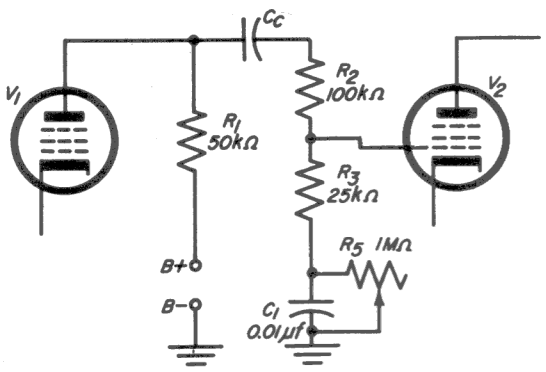


Fig. 34-16

would have if C_1 were not shunted by R_5. At in-between settings of the resistor, R_5C_1 has in-between amounts of effective impedance.

Since the effective impedance of R_5C_1 can be varied, the amount of bass boost can be varied. Rotating the shaft of the control from the position of minimum resistance to the position of maximum resistance causes the bass to increase in loudness without appreciable change in volume for middle and treble.

Continuously Variable Bass and Treble Control. The circuit shown schematically in Fig. 34-17*a* provides bass attenuation when the slider arm is at point *Q* and treble attenuation when the slider arm is at point *X*.

As the slider arm is moved up to point *Q*, bass attenuation occurs, not because less voltage at bass frequencies is developed across grid resistor R_2, but because *more voltage* at both middle and treble frequencies is developed across R_2. Thus bass is attenuated relative to the rest of the a-f band. Over-all volume will rise at the same time, because the level of the major portion of the a-f band is raised. The circuit is shown at *b* with the slider at point *Q*. The equivalent of this circuit is shown at *c*. Resistor R_1 and capacitor C_1 constitute an impedance Z_1 which is different for different frequencies because the reactance of C_1 is different for different frequencies. Impedance Z_1 and resistor R_2 constitute a voltage divider, the output voltage being developed across R_2.

The reactance, X_C, of capacitor C_1 (0.006 μf) at three reference frequencies in

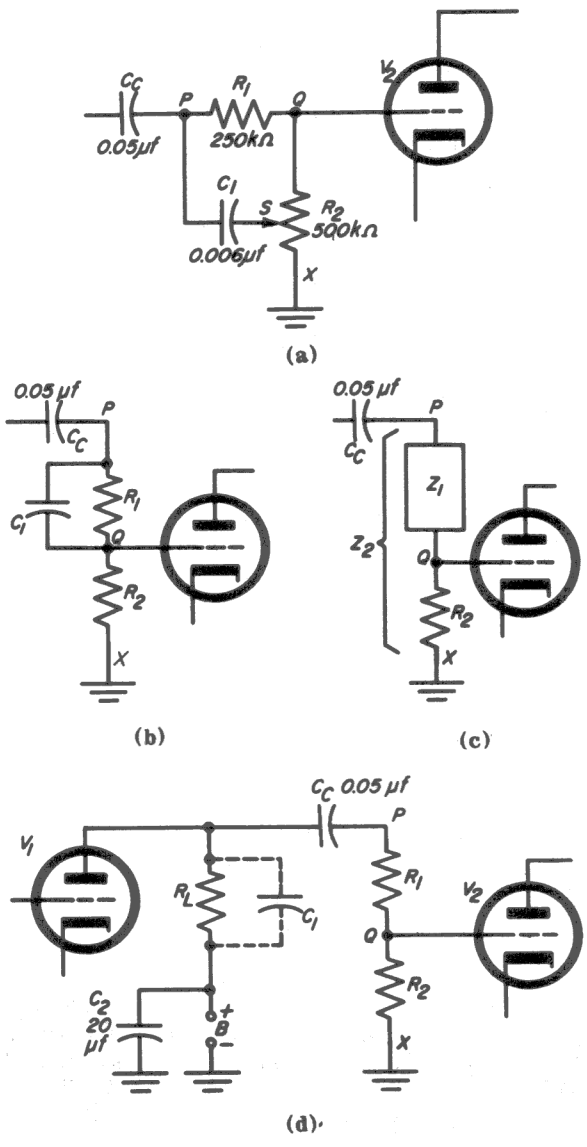


Fig. 34-17

the a-f band is:

530 k-ohms at 50 cps
26.5 k-ohms at 1,000 cps
2.65 k-ohms at 10,000 cps

The total, or input impedance of the voltage divider, $Z_2 = Z_1 + R_2$. The ratio of output voltage to input voltage is R_2/Z_2. At 50 cps, Z_2 = 729 k-ohms; at 1,000 cps, Z_2 = 526.4 k-ohms; at 10,000 cps, Z_2 = 502.65 k-ohms. At 50 cps, for 1 volt input, the output will be 500/729 volts, or 0.69 volts. At 1,000 cps, the output will be 500/526.4 volts, or 0.95 volts. At 10,000 cps, the output will be 500/502.65 volts, or 0.99 volts.

Thus, when slider arm *S* is at point *Q*, the impedance between *P* and *Q* is small for

middle and treble frequencies so that point Q is close to P, or high on the divider for middle and treble frequencies. Output voltage for middle and treble signals is relatively high. But for bass frequencies the impedance between P and Q remains large, so that Q is not as high up on the divider for bass. Output for bass is thus considerably lower than for the rest of the a-f band.

Now consider what happens when the slider is moved downward and approaches ground. The resistance between the lower plate of C_1 and ground becomes quite low; at zero resistance, C_1 is connected between point P and ground. In order to understand the action of C_1 now, it is necessary to consider the plate load resistor of the preceding voltage amplifier stage, as shown in the circuit of Fig. 34-17*d*.

Due to the negligibly small reactance of coupling capacitor C_c at treble frequencies, C_1 is effectively shunted across R_L, the plate load resistor of V_1 as shown by the dashed lines. (The low end of R_L is grounded for all audio frequencies by filter capacitor C_2.) The circuit now operates as a simple treble-cut capacitor when the switch is closed. The impedance of the plate load for treble is much lower than for middle and bass, so that gain of the stage for treble is reduced relative to gain for middle and bass. Therefore, treble is cut.

With C_1 no longer across R_1, bass and middle are equally attenuated by the voltage divider R_1R_2, which is now purely resistive.

When the slider is at any point between points P and Q, the action of the tone control will be intermediate between the two actions already described; that is, bass will be somewhat attenuated by relative boost of middle frequencies, and treble will be somewhat attenuated, relative to middle frequencies, by partial shunting of R_L. The nearer the slider is to point Q, the more bass will be cut and the less treble will be cut. The nearer it is to Point X, the less bass will be cut and the more treble will be cut.

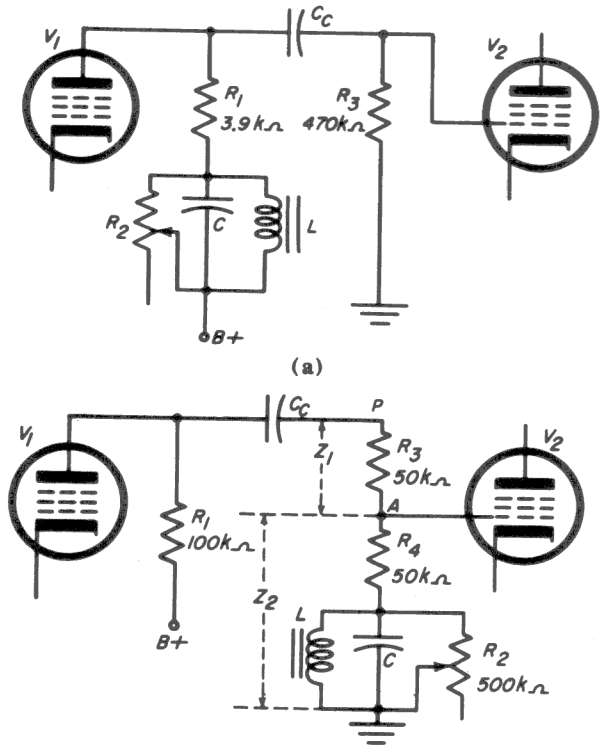


Fig. 34-18

34-3. TONE CONTROLS BASED ON RESONANCE

These controls take advantage of resonant rise of impedance to provide bass boost. They provide maximum boost at resonance, which is usually chosen to occur at 70 cps.

Figure 34-18*a* shows the resonant combination LC in series with the plate load resistor R_1. The impedance of LC is in series with the impedance of R_1, the two constituting the total plate load impedance Z_L. For frequencies at and near the bass resonant frequency, the impedance of LC is much higher than for other frequencies in the audio band. Therefore, the total impedance, Z_1, is much higher at and near the bass resonant frequency. Since gain of a pentode such as V_1 is approximately equal to G_mZ_L, the gain will be higher when Z_L is higher. (The resistor R_2 is a variable control and is shunted across L in order to control the amount of bass boost. When R_2 is zero, there is no bass boost; when R_2 is at maximum, there is maximum boost.) In Fig. 34-18*b*, the resonant circuit is used as part of a signal voltage divider shunted across the output circuit of V_1. The impedance of LC is very low for all frequencies except those in the bass

region. Therefore, the impedance Z_2 between point A and ground, is about 50,000 ohms, equal to impedance Z_1 between points P and A for all but bass frequencies.

As frequencies become lower and approach resonance, the impedance of LC rises, causing the impedance Z_2 to increase. A variable resistor, R_2, shunted across LC limits the rise of impedance, and also makes it adjustable. When R_2 is at zero resistance, the impedance of LC is zero and no bass boost results. When R_2 is at maximum, considerable increase in impedance Z_2 occurs at 70 cps and considerable bass boost occurs. At 70 cps, point A is higher up on the voltage divider than it is for middle and treble frequencies. Thus, R_2 in Fig. 34-18a is made variable to control the relative bass boost.

Circuits of this type can also be used to provide treble boost simply by choosing values of L and C that will resonate at a frequency slightly above the highest treble frequency to be reproduced.

Controls of this type are seldom used. The components are more expensive than those of equally effective capacitor types. The inductors tend to pick up a-c hum from the power line and the power transformer.

34-4. COMBINATION BOOST OR ATTENUATION CONTROLS

It is a considerable advantage if a tone control of an amplifier boosts when turned clockwise from midposition and attenuates when turned counterclockwise. When set at midposition, it neither boosts nor attenuates. The response of the amplifier is then approximately flat. Such controls are widely used on high-quality amplifiers.

Treble Boost or Attenuation Control. The tone control shown in Fig. 34-19 consists of two signal voltage dividers connected in parallel between point P and ground. One voltage divider – $C_1R_2C_2$ – is reactive, due to the capacitors. The other, R_3R_4, is resistive. The variable resistor R_2, as shown, is a potentiometer.

Let us first consider the two voltage dividers independently, as though the connec-

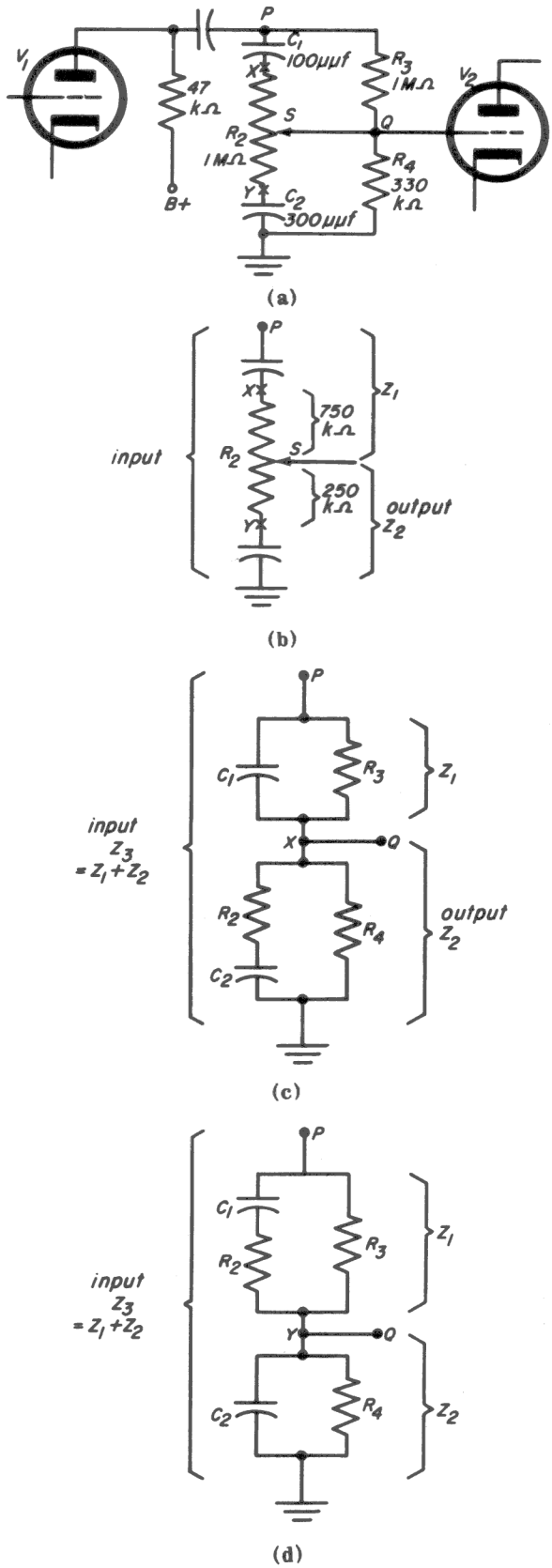


Fig. 34-19

tion between the slider arm S and point Q were broken. In the purely resistive voltage divider, the ratio of R_4 to R_3 is 1:3. The ratio of R_4 to the total resistance ($R_3 + R_4$) is 1:4. For a signal applied across the input (point P to ground), only 1/4 of the signal will appear across the output, R_4. This applies to all frequencies, since the divider, being purely resistive, does not offer different impedances to different frequencies. For all frequencies, 1 volt at the input produces 0.25 volt at the output.

In the case of the reactive voltage divider shown separately at *b*, only at the physical midpoint of the resistor track (that is, the 50 percent rotation position of slider arm S) will the output be 1/4 of the input for all frequencies. The *taper* of the resistance track is such that when the slider is at this position, the amount of resistance between S and point X is 750 k-ohms; between S and point Y, it is 250 k-ohms. If we call the upper portion (750 k-ohms) R_x and the lower portion (250 k-ohms) R_y, then the ratio of R_y to R_x is 1:3 and the ratio of R_y to the total resistance ($R_y + R_x$) is 1:4. In the case of the capacitors, the ratio of the reactance of C_2 at any frequency to the reactance of C_1 at the same frequency is 1:3, and the ratio of the reactance of C_2 to the total reactance at the same frequency, is 1:4. For all frequencies in the a-f range, 1 volt across the input produces approximately 0.25 volts across the output.

The important thing to notice about the midpoint setting of slider arm S is that in this setting, and *only* in this setting, do the resistances R_y and R_x have the same ratio to each other as the reactances of C_2 and C_1. When this condition exists, the response of the reactive voltage divider is the same for all frequencies. All applied a-f signals, regardless of frequency, are attenuated at the output, S, to 1/4 their amplitude at P. The slider arm is therefore in the *flat* position, where treble is neither boosted nor attenuated relative to the rest of the a-f band.

Leaving the slider arm in this position, let us now restore the connection between the output terminals of the two voltage dividers, that is, between S and Q. Since both voltage dividers attenuate signals of all frequencies by the same amount, any signal applied to P will normally produce the same output voltage at S as at Q. Therefore, neither output circuit will load the other, any more than two batteries having the same voltage would load each other if connected in parallel. In brief, the two voltage dividers do not modify each other's voltage distribution when S is in the midpoint position or flat response position.

But when S is in any position other than the midpoint position, the two voltage dividers cannot be considered separately because they now modify each other's voltage distribution, for they no longer have the same output-to-input ratios. What is more, they alter the distribution by different amounts for different frequencies. When S is moved up towards point X, the ratio of output voltage to input voltage rises for treble signals, while it remains substantially constant for middle and bass signals. Why this is so can be seen if we draw the equivalent circuit. Fig. 34-19*c*, that results when S is moved all the way up to point X, the position of maximum treble boost. We must now consider both dividers as one complex voltage divider, and note that the impedances of its upper portion, Z_1, and of its lower portion, Z_2, do not have the same ratio for a treble frequency, such as 20,000 cps as they have for a middle frequency, such as 1,000 cps.

In the case of a 20,000-cps signal, the impedance Z_1 is the result of computing vectorially the value of the reactance of C_1 (at 20,000 cps) in parallel with $R3$; that is, the vector sum of 79.5 k-ohms in parallel with 1,000 k-ohms. We may take this combination to equal 79 k-ohms. For the lower portion of the voltage divider, the impedance Z_2 consists of R_4 in parallel with the series combination of C_2 and R_2. This combination equals 26.5 k-ohms (the reactance of C_2 at 20,000 cps) added vectorially to R_2, 1,000 k-ohms. It comes out so close to 1,000 k-ohms that no significant error arises from calling it precisely 1,000 k-ohms. This, in parallel with 330 k-ohms, making Z_2 as approximately 248 k-ohms.

Now, referring again to Fig. 34-19*c*, we have the ratio of the output impedance Z_2 *to* the input impedance Z_3 (the total impedance, $Z_1 + Z_2$), in simplified form:

$$\frac{Z_2}{Z_3} = \frac{248}{79 + 248} = 0.76$$

The ratio of the impedances is such that if a 1-volt signal at 20,000 cps is applied across the input of the complex voltage divider, the output voltage will be 0.76 volts while the slider is at point *X*.

Using the same approach to find the impedances Z_1 and Z_2 at 1,000 cps, we take the reactance of C_1, now equal to 1930 k-ohms, in parallel with R_3, and find the vectorial sum to be approximately 800 k-ohms, for Z_1. To find Z_2, we take the reactance of C_2 (now equal to 530 k-ohms) in series with 1,000 k-ohms, and obtain the vector sum for the combination, 1086 k-ohms; then we find the approximate value of this sum in parallel with 330 k-ohms. The result is 253 k-ohms, the value of Z_2.

With values of 800 k-ohms for Z_1 and 253 k-ohms for Z_2, the output voltage, for an applied signal of 1 volt at 1,000 cps, is:

$$\frac{Z_2}{Z_3} = \frac{253}{800 + 253} = 0.24 \text{ volt}$$

Contrasting the two results, we can see that when slider *S* is at point *X*, the output for a 1-volt signal at 20,000 cps is 0.76 volt, but for a 1-volt applied signal at 1,000 cps, the output is only 0.24 volt. Thus the control can boost treble, relative to the middle range by a factor of slightly more than three to one.

To produce a treble cut, the slider arm is moved down from the flat position toward point *Y*. Figure 34-19*d* shows the equivalent circuit.

Using the same method as that outlined for the case of treble boost, we again find the impedances of the two portions of the complex divider for a signal at 20,000 cps and a signal at 1,000 cps. We find that at 20,000 cps, Z_1 equals 501 k-ohms and Z_2 equals 26.4 k-ohms. The output for 1-volt input at 20,000 cps in simplified form is:

$$\frac{Z_2}{Z_3} = \frac{26.4}{501 + 26.4} = 0.05 \text{ volt}$$

At 1,000 cps, impedances Z_1 and Z_2 are found to be, respectively, 997 k-ohms and 329 k-ohms. For 1-volt input at 1,000 cps, the output voltage is:

$$\frac{Z_2}{Z_3} = \frac{329}{997 + 329} = 0.248 \text{ volt}$$

If the impedances Z_1 and Z_2 are calculated for a frequency in the bass range, it will be found that for any setting of the potentiometer R_2, the output of a complex voltage divider is very close to 0.25 volt for a 1-volt input. Thus, it may be seen that the control varies the attenuation of treble signals only, leaving middle and bass signals at a fixed level of attenuation. Since treble signals may be attenuated less than middle and bass signals, or more than middle and bass signals, treble tones can therefore be boosted or cut relative to the rest of the a-f range.

Bass Boost or Attenuation Control. The tone control of a diagram of Fig. 34-20 offers a high degree of either boost or attenuation of bass frequencies. The control consists of a voltage divider that contains two resistors and two variable impedances, Z_1 and Z_2 in series (Fig. 34-20*b*); the output signal is taken off at the junction of Z_1 and Z_2. The impedances are varied by the setting of the potentiometer, R_3 (shown in Fig. 34-20*a*).

Let us call the portion of R_3 between the slider *S* and point *A*, R_a, and the portion between *S* and *B*, R_b. Impedance Z_1 consists of R_a in parallel with C_1. Impedance Z_2 consists of R_b and R_4 in parallel with C_2. As the slider arm is moved upward, it lowers Z_1 for bass frequencies while simultaneously increasing Z_2. As it moves downward, it increases Z_1 for bass frequencies while simultaneously decreasing Z_2. Let us call the *total* impedance, of the voltage divider, Z_3 (shown at *b*), and let Z_4 be the

output impedance that is constituted by Z_2 and R_5.

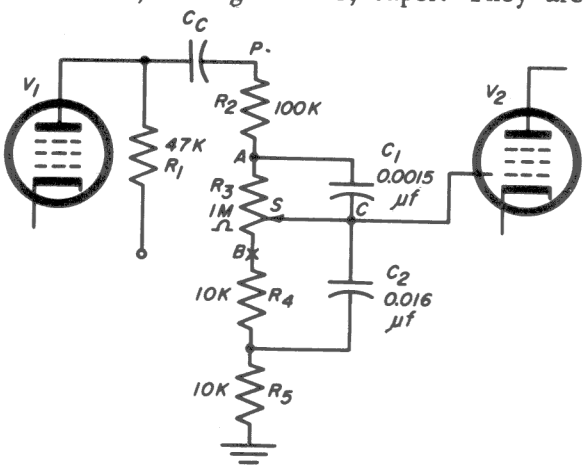
The control is usually followed by a high gain voltage amplifier stage, because the tone control network introduces a rather heavy loss for middle and treble range frequencies, the output voltage for them being slightly less than one-tenth of the input voltage. It introduces a variable loss for bass frequencies, and this loss can be made either much less than the loss for middle and treble, or much more. This is equivalent to boosting bass or cutting bass, relative to the rest of the a-f range.

When slider arm S is at the midpoint of the resistance track, the control is in an approximately flat position. The taper of the resistance track is such that R_a now equals 900 k-ohms, while R_b equals only 100 k-ohms. These values for R_a and R_b are used because they can be found in the standard audio, or logarithmic, taper. They are not ideal. Ideal values require that when the control is in the flat response position, R_a should be to R_b plus R_4 as the reactance of C_1, at any frequency is to the reactance of C_2 at the same frequency, or as 1,060 k-ohms is to 99.5 k-ohms.

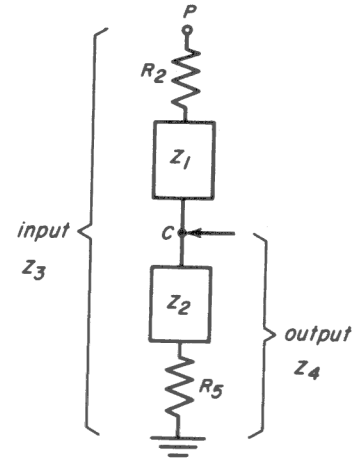
The standard taper is reasonably close and introduces no important error.

An ideal taper would produce, when the control is at the midpoint position, equal output voltages for two signals of widely different frequencies, provided each of the two signals had the same input voltage. We can see how much error the standard taper causes by testing the output of the control at 50 cps and at 10,000 cps when 1 volt is applied in each instance.

To make this comparison, we must find the value, at 50 cps, of impedances Z_1, Z_2,



(a)



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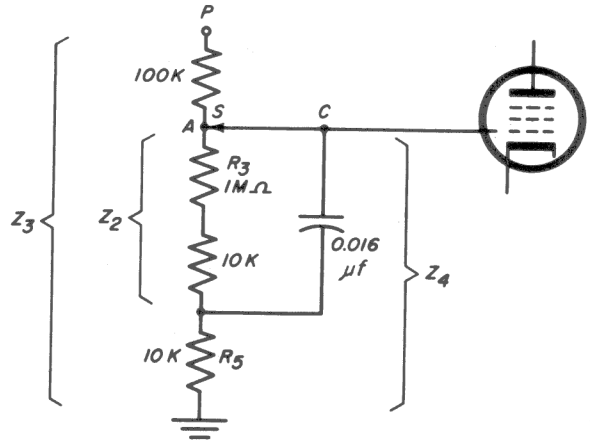
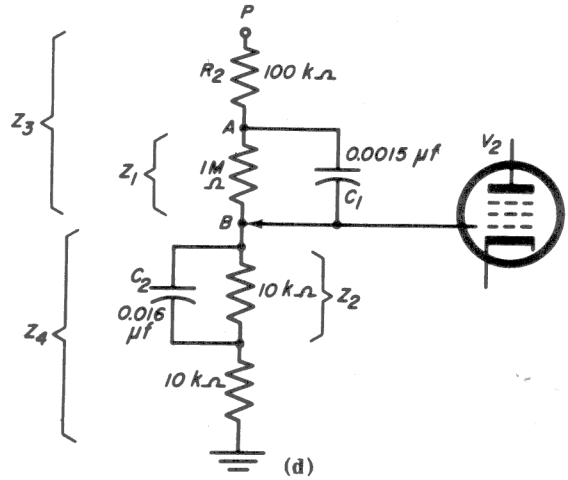


(c)



(d)

Fig. 34-20

Z_3, and Z_4 (Fig. 34-20). Then we find the ratio of output impedance to input impedance, Z_4/Z_3. This fraction is the same as the ratio of output voltage to applied input voltage, since the voltages are directly proportional to the impedances across which they are developed. Then we repeat the procedure for a signal at 10,000 cps. Then we compare the two output voltages, to see how much difference there is.

Having outlined the procedure, let us do it. If you wish to follow the calculations in great detail, use the formulas given in the Appendix to check the values of Z_1 and Z_2. The values are given here in abbreviated form in order to keep the explanation as clear and simple as possible.

At 50 cps:

$Z_1 = R_a$ (900 k-ohms) in parallel with X_{C1} (2,120 k-ohms) = 828 k-ohms

$Z_2 = R_b + R_4$ (100 k + 10 k) in parallel with X_{C2} (200 k-ohms) = 96.4 k-ohms

$Z_3 = R_2 + Z_1 + Z_2 + R_5 = 100 + 828 + 96.4 + 10 = 1034.4$ k-ohms

$Z_4 = Z_2 + R_5 = 106.4$ k-ohms

$Z_4/Z_3 = 106.4/1034.4 = 0.103$

This shows that 1 volt applied across the input would produce 0.103 volts across the output, at 50 cps.

At 10,000 cps:

$Z_1 = R_a$ in parallel with X_{C1}

= 900 k in parallel with 10.6 k

= 10.5 k-ohms

$Z_2 = R_b + R_4$ (100 k + 10 k) in parallel with X_{C2}

= 0.99 k-ohms

$Z_3 = R_2 + Z_1 + Z_2 + R_5 = 100 + 10.5 + 0.99 + 10 = 121.49$ ohms

$Z_4 = Z_2 + R_5 = 0.99 + 10 = 10.99$ ohms

$Z_4/Z_3 = 10.99/121.49 = 0.09$

This shows that 1 volt applied across the input would produce 0.09 volt across the output at 10,000 cps. The difference between the two output voltages is 0.103-0.09, or 0.013 volt, showing that the standard taper produces a reasonably small error when the slider S is in the midpoint position. This error can be eliminated by turning the slider shaft away from the center position in a counterclockwise direction until the ratio of R_a to $R_b + R_5$ is in the proportion of 1,060 k-ohms to 99.5 k-ohms approximately, the ratio which the ideal taper would have in the center position. Thus an actual flat-response position exists for the standard taper, but it is slightly off center. The panel scale for such a control would be marked accordingly, with the flat-response mark slightly off center.

Next, let us compare the output at 50 cps and at 10,000 cps, with the control set to the bass boost position--with the slider at point A. The equivalent circuit for this condition is shown at c. Note that C_1 is shorted out, making Z_1 equal to zero.

At 50 cps:

$Z_1 = 0$ ohms

$Z_2 = R_3 + R_4$(1000 k + 10 k) in parallel with X_{C2} (200 k) = 192.4 k-ohms

$Z_3 = R_2 + Z_1 + Z_2 \times R_5 = 100$ k + 0 + 192.4 k + 10 k = 302.4 k-ohms

$Z_4 = Z_2 + R_5 = 192.4$ k + 10 k = 202.4 k-ohms

$Z_4/Z_3 = 202.4/302.4 = 0.669$

That is, 1 volt at 50 cps, applied across the input will produce 0.669 volts across the output when the slider is at A.

At 10,000 cps:

$Z_1 = 0$ ohms

$Z_2 = R_3 + R_4$ (1,000 k + 10 k) in parallel with X_{C2} (0.995 k) = 0.995 k-ohms

$Z_3 = 100$ k + 0 + 0.995 k + 10 k = 110.995 k-ohms

$Z_4 = 10$ k = 0.995 k = 10.995 k-ohms

$Z_4/Z_3 = 10.995/110.995 = 0.099$

At 10,000 cps, 1 volt applied across the input of the voltage divider will produce 0.099 volt across the output, when the slider is at *A*. But for the same position of the slider the output at 50 cps is 0.669 volt, almost 6.8 times as much as at 10,000 cps. Thus, relative to a signal at 10,000 cps, a signal at 50 cps is very greatly boosted.

When the slider is at *B*, the bass-attenuate position, the equivalent circuit is as shown at *d*. The output voltage at 50 cps should be much less than the output voltage at 10,000 cps.

At 50 cps:

$Z_1 = R_3$ in parallel with X_{C1} (2,120 k)

= 904.4 k-ohms

$Z_2 = R_4$ in parallel with X_{C2} (200 k) = 10 k-ohms

Z_3 = 100 k + 904.4 k + 10 k + 10 k = 1,024.4 k ohms

Z_4 = 10 k + 10 k = 20 k-ohms

$Z_4/Z_3 = 20/1{,}024.4 = 0.0194$

The output voltage at 50 cps for 1 volt applied across the input, is 0.0194 volt with the slider in the bass-attenuate position.

At 10,000 cps:

$Z_1 = R_3$ in parallel with X_{C1} (10.6 k)

= 10.6 k-ohms

$Z_2 = R_4$ in parallel with X_{C1} (0.995 k) = 0.995 k-ohms

Z_3 $R_1 + Z_1 + Z_2 + R_5$ = 100 k + 10.6 k + 0.995 k + 10 k = 121.595 k-ohms

Z_4 = 10 k + 0.995 k = 10.995 k-ohms

$Z_4/Z_3 = 10.995/121.595 = 0.09$

At 10,000 cps, when 1 volt is applied across the input, the output voltage is 0.09 volt. But the output voltage at 50 cps is only

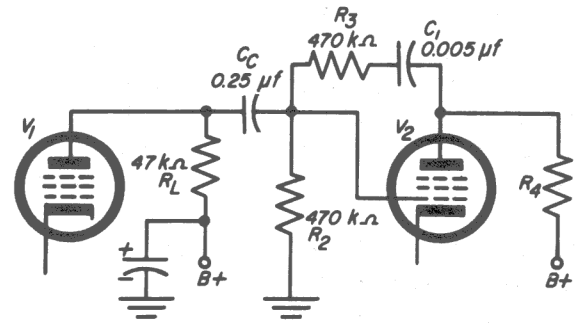


Fig. 34-21

0.019 volt, or about 1/5 as much as at 10,000 cps.

34-5. TONE CONTROLS BASED ON INVERSE FEEDBACK

As you may recall, inverse, or negative, feedback applies part of the output signal of an amplifier or amplifier stage, to the input in such phase as to oppose the normal input signal. The feedback signal, being of opposing phase, cancels part of the input signal, thereby making the input signal effectively smaller. Since the *effective* signal applied to the grid of the stage is smaller, the output of the stage is less. Inverse feedback therefore reduces the gain of an amplifier stage. However, it also reduces any distortion introduced into the signal by the stage because it feeds the distortion component of the signal back in such phase as to cancel itself partially. If the amount of feedback is large, the cancellation of distortion can be almost total. Inverse feedback can make an amplifier stage very nearly perfect. But the amount of inverse feedback required to do so also reduces the effective input signal. Therefore adequate input signal must be available to drive a stage employing a large amount of negative feedback. This is an easy requirement to meet. Modern resistance-coupled amplifiers can provide a considerable amount of gain, leaving a generous surplus for circuits that operate by introducing a loss.

If a feedback path or loop, as it is called, is modified in any way that causes it to feed back less voltage at one frequency than at another frequency, the gain of the stage will be higher for the frequency at which less voltage is fed back. For example, consider Fig. 34-21. The feedback loop from the plate

of V_2 to the grid of V_2 consists of R_3 and C_1. If a positive-going signal is applied to the grid of V_2, a negative-going signal will simultaneously appear at the plate. Since C_1, R_3 and grid resistor R_2 constitute a voltage divider, a fraction of the negative-going output signal will be applied to the grid. The negative-going signal will cancel part of the positive-going signal, making a smaller effective signal on the grid, and lowering the tube's output voltage. This is equivalent to reducing the gain of the tube.

If a complex signal of many frequencies is applied to the grid of the tube, each frequency will be opposed by a feedback signal of opposite phase. A high-frequency input signal will be opposed by a feedback signal of the same frequency, and gain for the high-frequency signal will be reduced in proportion to the percentage of the output signal fed back through the voltage divider. A low-frequency input signal will be opposed by a feedback signal of the same frequency, and gain for the low frequency signal will be reduced in proportion to the percentage of the output signal fed back through the voltage divider.

If capacitor C_1 had the same reactance for all frequencies, the percentage fed back by the voltage divider would be the same for all frequencies. But C_1 has a different reactance for different frequencies. By choosing the value of C_1 so that it will have a high reactance to bass, but a relatively low reactance to middle and treble, it can be made to feed back very little opposing signal at low frequencies, so that the lower a frequency is, the less it will oppose itself by feedback, and the higher the gain of the stage will be. Bass boost will result.

In calculating what the percentage of the feedback signal will be, the designer of an amplifier takes into account the fact that, as far as the feedback signal is concerned, C_c and R_L are in series, and are shunted across R_2, so that the impedance from grid to ground is lower than that of R_2 alone. The reactance of C_c will also cause the resultant impedance to vary with frequency. The coupling capacitor C_c is therefore chosen to be quite large, so as to minimize the variation of impedance due to it.

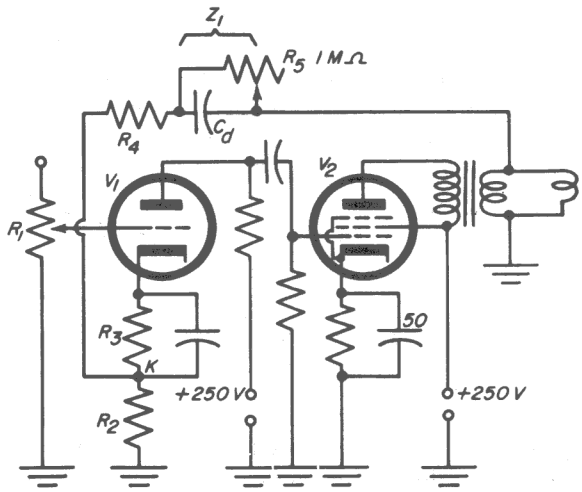


Fig. 34-22

Over-all Feedback. In the circuit just considered, feedback was confined to a single stage. It is also possible for the feedback loop to be extended over two or more stages if care is taken that the stages do not introduce enough phase shift to cause the feedback to become positive at some frequencies.

Since the phase relationship at the plate of the second stage may be in phase with input signal voltage at the grid of the first tube, coupling between these two places may introduce positive feedback. Depending upon the nature of the coupling resistors and capacitors, positive feedback of some of the a-f range may occur.

Figure 34-22 shows a simple amplifier with over-all feedback, that is, feedback from the amplifier's output transformer to the cathode of the input tube. Variable bass boost is included in the loop. Note that one end of the output transformer's secondary is grounded. The secondary voltage may be used as the feedback voltage. The correct end of the secondary must be grounded, or the polarity of the voltages will not be opposite to the signal voltages at point K, to which the feedback voltages are applied.

The combination of R_4, R_5, and C_d is inserted in the feedback path as shown, and modifies the feedback voltages appropriately. The resistor, R_4 is chosen to limit the maximum amount of feedback to a fraction that will not be excessive. The capacitor C_d is

chosen to have a high reactance at bass frequencies, so as to reduce the amount of bass feedback relative, to middle and treble and thus cause bass boost. The resistor R_5 is a variable shunt to limit the amount of reactance to bass that C_d, can insert in the path. When R_5 is zero, C_d has no effective reactance, and no bass boost results. When R_5 is at maximum, C_d has high reactance, and full bass boost results. At in-between settings of R_5, proportional amounts of bass boost result.

The fact that the feedback signal is applied to the input cathode instead of the input grid does not matter, so long as the phase of the applied feedback signal is opposite to that which would appear across R_2 as a result of current flow caused by the normal input signal. The cathode provides a convenient way of introducing the feedback signal into the tube without modifying the action of the input volume control.

Note that R_2 is unbypassed. If it were bypassed, the feedback signal would be bypassed to ground, and would not cause the potential at point K to vary. The capacitor would defeat the action of the feedback signal. However, R_2 may be *selectively* bypassed – that is, bypassed for a limited range of frequencies for which feedback is not desired. If it is desirable to boost the treble response of the amplifier, R_2 may be bypassed by a properly-chosen capacitor which, for treble frequencies only, has a reactance low enough to bypass a fraction of the treble feedback signals. With less treble feedback, gain of the amplifier for treble frequencies will be higher. Generally speaking, for minimum degeneration, the reactance of the capacitor should be one-tenth the value of the resistor at the lowest audio frequency to be passed.

34-6. LOUDNESS CONTROLS

Our hearing sensitivity varies widely for different frequencies at different volume levels. The famous Fletcher-Munson curves, presented in Fig. 34-23, reveal that at very high levels, such as might prevail close to a full symphony orchestra playing at normal volume, the ear hears bass, middle, and treble tones with almost equal loudness.

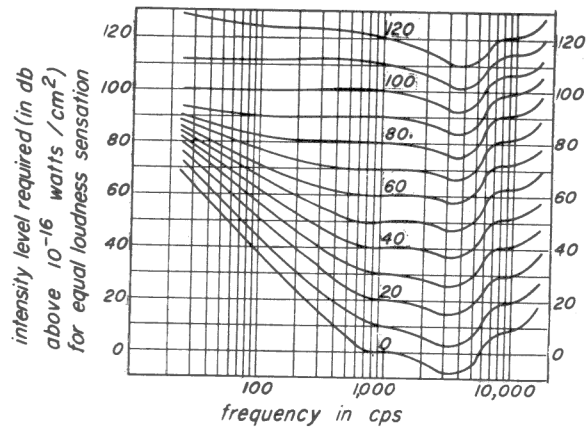


Fig. 34-23

But as one moves away from the orchestra, toward the rear of the concert hall, the bass seems to drop out very rapidly, while the treble drops less rapidly, and the middle tones diminish least rapidly. The curves show how much more intense bass and treble need to be to *seem* to retain the same proportion to middle tones as the overall volume decreases. In other words, at low volumes, more sound power is needed at bass and treble frequencies to make them sound as loud as the middle frequencies.

If the program is recorded or broadcast and reproduced in the home, it is generally reproduced at a level much lower than that of the original sound in the concert hall. Under these conditions, the music seems to be lacking something. The bass sounds weak and unsatisfactory, even though a sound-measuring instrument would show that it has the same proportion to middle and treble as it had originally. If the amplifier is powerful, so that we can turn the music up loud, the bass again seems to come back to its original proportion. Actually, it is our hearing that creates this effect. The ear simply does not hear bass tones well at low volume levels. This is why owners of high fidelity amplifiers and powerful wide range loudspeakers usually play their recordings at very high levels. A startling realism results when wide-range distortionless equipment reproduces sound at its original level.

But few homes have rooms large enough, or neighbors tolerant enough, to warrant reproducing sound at high levels for any length of time. It is generally necessary to turn down the volume, to a level far below that of the original sound. The Fletcher-Munson curves show that, as volume is lowered, the

bass must be lowered far less (that is, it must be boosted relatively) in order to sound to the ear as though it had the same proportion to middle tones that it had at full volume. Treble tones also require less attenuation as volume is lowered. However, they need not be boosted relatively to so great a degree as bass.

Designers have devised a number of volume control systems that insert some degree of compensation – of unequal attenuation for bass, middle and treble – automatically, as volume is turned down. Such controls are a combination of volume and tone controls, since they not only adjust over-all loudness, but relative loudness as well. They are intended to eliminate the need for resetting separate tone controls each time the over-all volume is adjusted. They are generally called loudness controls.

Let's consider two types. The first, shown schematically in Fig. 34-24*a*, consists of two potentiometers on one shaft, arranged to turn in unison, so that when one is at maximum, the other is at maximum; when one is at minimum, the other is at minimum; when one is at midresistance, the other is at midresistance, and so on. Together with additional resistors and capacitors, they constitute two reactive voltage dividers in cascade. Connection in cascade means that the signal applied to the input of the first voltage divider is taken from its output (slider arm S_1) and applied to the input of the second voltage divider, after which it is taken from the output of the second, slider arm S_2. By this arrangement, the effects upon the input signal are multiplied, rather than added. If each voltage divider offers a maximum bass boost of 4, the combination offers a maximum bass boost of 4 x 4, or 16 times, relative to middle frequencies.

By just looking at the first voltage divider in the figure, and visualizing the slider S_1 at point Q, one can see that at this setting, the circuit is the equivalent of the bass boost arrangement of Fig. 34-15*b*. The second voltage divider will be another such circuit. Points Q and Y will be much higher up on the dividers for bass than for middle or treble, due to high reactance of the capaci-

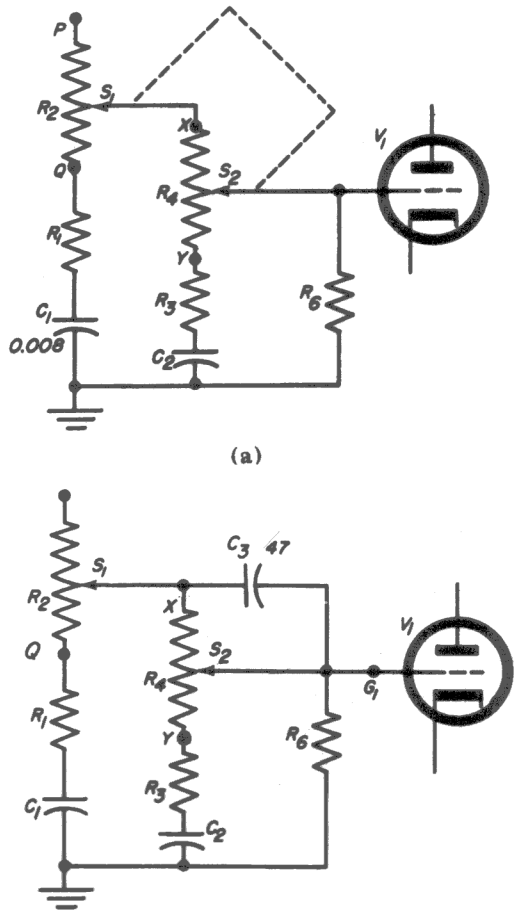


Fig. 34-24

tors at low frequencies. But as the slider arms move upward towards points P and X, contact points S_1 and S_2 become less high for bass relative to middle and treble because the proportion of resistance to reactance changes. At points P and X, the inputs to the dividers, bass, middle, and treble frequencies will all be at the same high level; all will be loud, and none will be boosted relative to the others.

A slight amount of treble boost may be added to the output, as shown in Fig. 34-24*b*, by adding capacitor C_3, which is chosen to have a relatively low reactance for treble, but high reactance for bass and middle frequencies. Treble boost *gradually increases* as the slider moves downward because the impedance between X and G_1, for middle and bass, increases as the slider inserts more resistance between X and G_1. But the impedance does not increase nearly as much for treble, because the low reactance of C_3 at treble frequencies holds the impedance between the two points to a small amount.

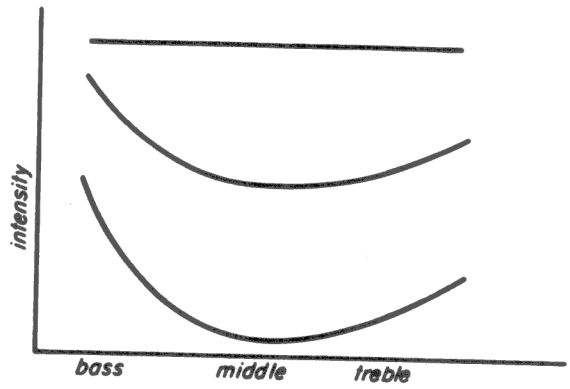


Fig. 34-25

Thus, as the shaft of the dual control is turned counterclockwise, the middle frequencies are attenuated, but the bass and treble are proportionately less attenuated. The effect of the control upon the characteristic of the amplifier is to pull down the middle part of the characteristic, leaving the ends curled upward, the bass more than the treble. If the characteristics of the amplifier were drawn for a number of different settings of the control – for different amounts of counterclockwise rotation – the resulting characteristics would have shapes roughly resembling the Fletcher-Munson curves. As the volume was reduced more and more, the curves would be progressively bent further away from the flat line shape. But this is just the change that the ear needs, in order to hear the characteristic as flat, when sound is reproduced at less than its original level. Figure 34-25 shows the effect of the control, at three different volume levels upon the characteristic of a high-quality amplifier.

Single Potentiometer Loudness Control. The arrangements, shown schematically in Fig. 34-26 uses a tapped 1-megohm potentiometer with added RC networks to produce an effect resembling that of two voltage dividers in cascade. The external RC networks are contained in a small printed-circuit housing (indicated by the dashed line) and connected to the potentiometer as shown in Fig. 34-26*a*.

The cascade action may be seen by noting the equivalent circuits when the slider is at points *X* and *Y*. When it is at point *X*, the equivalent circuit is that shown at *b*. The network R_1, R_4, and C_3 constitutes a voltage divider similar to that in Fig. 34-15*b*, and produces bass boost. Point *X* is

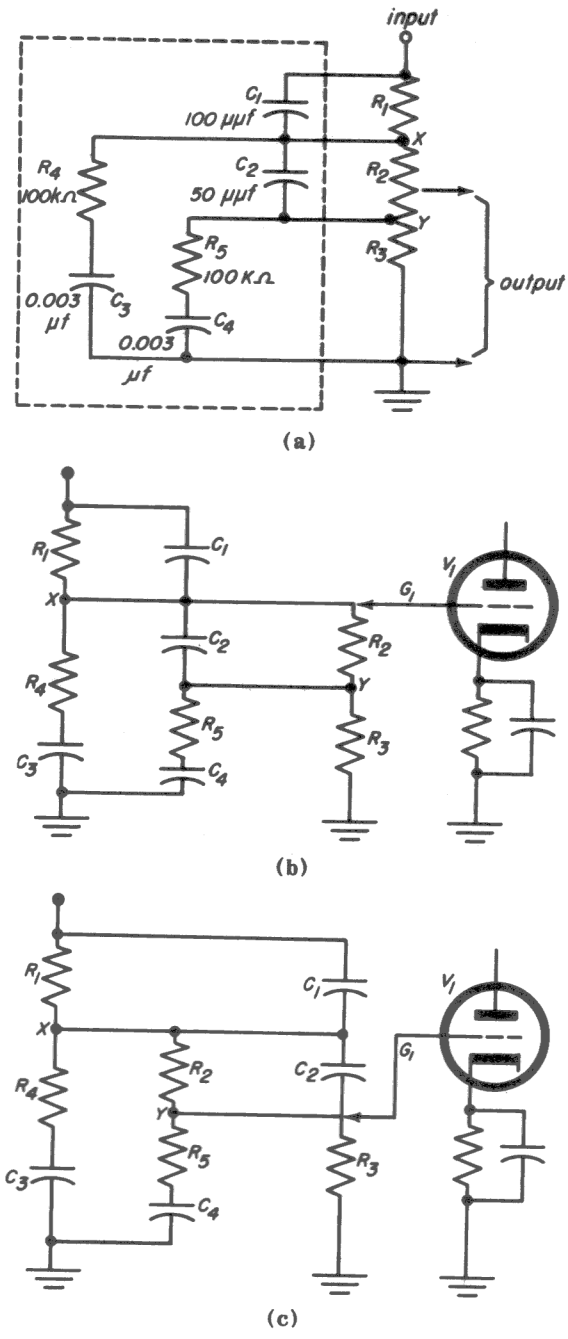


Fig. 34-26

higher up on the divider for bass than for middle frequencies, due to the higher reactance of C_3 at bass frequencies. The capacitor C_1, shunting R_1, provides a slight amount of treble boost, by letting treble signals reach G_1 by a path lower in impedance (for treble only) than R_1. This puts G_1, for treble signals, at a point higher up on the divider. Thus a greater proportion of treble voltage will appear between grid and ground, across R_2 and R_3. Capacitor C_2 does not bypass treble signals from grid to ground,

because it has less capacitance than C_1 and because it is largely isolated from ground by resistors R_5 and R_3.

Resistors R_2 and R_3 provide a d-c path between grid G_1 and ground; otherwise bias between G_1 and cathode could not be maintained. R_5 and C_4 have little effect upon the circuit, with the slider in its present position, because the relatively high resistance of R_2 and the high reactance of C_2 isolate them from the signal. The over-all effect of having the slider in this position is that middle frequencies are attenuated considerably, due to the voltage drop across R_1; treble is attenuated less (boosted slightly) due to C_1; and bass is attenuated very little (boosted considerably) due to the reactive effect of C_3.

When the slider is moved downward until it reaches Y, the equivalent circuit becomes that shown at c. We can see at once that it is the same as two reactive voltage dividers in cascade. (Compare this illustration with Fig. 34-24.) The output of the first divider (R_1, R_4, C_3), taken off at X, is applied to the input of the second divider (R_2, R_5, C_4), and taken off at Y. The bass boost is now cascaded, and middle frequencies are heavily attenuated by the large voltage drop across R_1 and R_2 which leaves only a small voltage across R_3. Treble is boosted slightly above the level of middle frequencies by the action of C_1 and C_2 in series. Although these two capacitors in series have less effective capacitance than either one alone, they are shunted across a larger amount of resistance; relatively, they offer treble signals a lower impedance path to G_1 than R_1 and R_2 offer to middle frequencies. C_2 is included in the circuit to keep C_1 from boosting treble excessively at low volume levels.

The over-all effect of the control is to attenuate middle frequencies more than bass and treble, with the attenuation for middle frequencies becoming progressively greater than for the rest of the audio range as slider moves downward. In effect the amplifier's characteristic curls up at the ends, as required by the ear, when the control is rotated to lower the over-all volume.

It should be noted that, with this loudness control, the cascade effect does not begin until the shaft has been rotated enough to bring the slider down below point X. Consequently, the cascading is not as effective as in the first control. With the first control, the maximum difference in level possible between middle and bass is more than 40 dbv, whereas with the second control it is approximately 20 dbv.

Both controls make a marked difference in audibility of the entire audio range when reproduction is at low levels.

If we use the term *loudness* to mean the ear's impression of relative sound volumes, and the term *intensity* to mean the actual relative volumes, we see that loudness and intensity differ. It is because these highly compensated controls attempt to create a flat *loudness* characteristic for all levels, by greatly bending the actual intensity characteristic, that they are called *loudness controls.*

There are many high-fidelity enthusiasts who feel that loudness compensation is wrong in principle; that since bass fades out rapidly as one moves away from a real orchestra, it should be allowed to fade rapidly as one attenuates the volume of an amplifier; that this kind of compensation is really deliberate frequency distortion.

Whether it is good or not really depends upon the taste of the listener. If one likes it, it is good. If one doesn't, it is not. It should be available for those who want it, who like to hear all the instruments in an orchestra, even if their relative intensities are altered.

APPENDIX A – IMPEDANCE OF RESISTOR –CAPACITOR COMBINATIONS

Occasionally in this lesson, for the sake of brevity and simplicity, the combined effect of a resistance and a capacitive reactance in series has been presented as though the two quantities need only to be added to produce their resultant impedance. This procedure is suitable when analyzing the *principle* of certain tone controls, but not when an accurate *quantitative* analysis is undertaken. Adding gives only a rough approximation of the combined impedance.

The precise impedance of a series resistor-capacitor combination, would have to be known if one were, for example, designing a tone control. This impedance can be found from a formula that you learned in the lesson on a-c circuits. We recall it to you now:

$$Z = \sqrt{R^2 + X_c^2}$$

To see how the results obtained by simple adding differ from the results obtained by using the correct formula, we can apply the two methods to the voltage divider in Fig. 34-15*b*. R_2 and R_3, totaling 125 k-ohms, are in series with C_1, whose reactance at 50 cps is 318 k-ohm.

Let us first treat the reactance of C_1 as though it were a simple resistance, R_x, in series with the 125 k-ohms, the total of R_2 and R_3. See Fig. 34-27*a*. The total resistance of R_2, R_3 and R_x is 443 k-ohms. If a sine-wave voltage, E_1, is applied between point E and ground, a sine wave of lower voltage, E_2, is present between point F and ground.

$$E_2 = \frac{318}{443} \times E_1, \text{ or } 0.72 \times E_1$$

E_2 is in phase with E_1, as shown at *b* in the figure. As E_1 reaches its peak, P, E_2 reaches its peak, P'.

Now let us treat the reactance of C_1 not as a resistance, but correctly as a capacitive reactance, shown at *c*. When a sine wave, E_1, is applied between point E and ground, a varying charge develops across C_1. The variation is a sine wave. It tries to follow the voltage across point E and ground. But due to the time constant of C_1 and the combined resistance of R_2 plus R_3, the voltage at F lags the voltage at E. (Stated differently, it takes time for the limited number of electrons that can flow through the resistance of R_2 and R_3 per unit of time, to alter the charge on C_1.)

The net effect of the time constant is that voltage E_2 at point F, is not in phase with voltage E_1. Voltage E_1 reaches its peak, P, before voltage E_2 reaches its peak, P'. The phase and approximate amplitude relationship is shown at *d*. The phase of E_2 is said to be shifted with respect to the phase of E_1.

As a consequence of this phase shift, the maximum voltage drop across the resistors does not occur at the same time as the maximum voltage drop across the reactance of C_1. Therefore the voltage drops cannot be directly added.

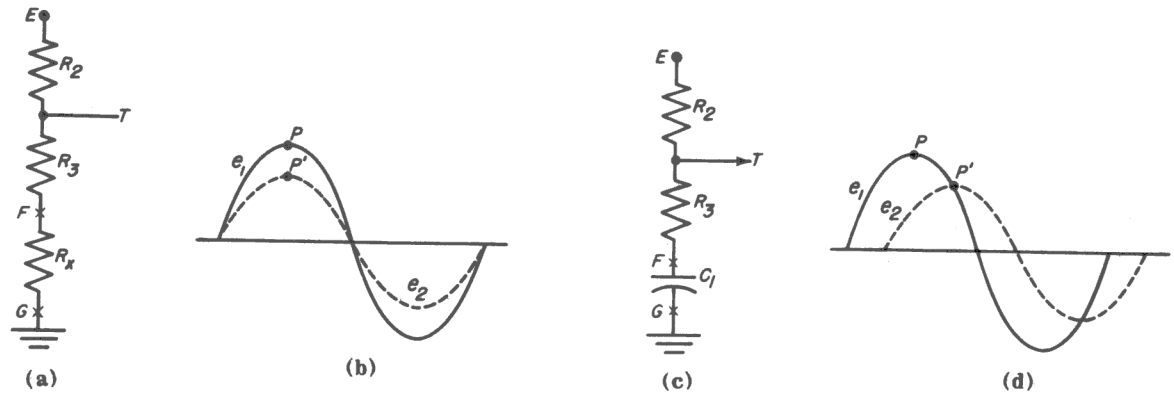


Fig. 34-27

Since it is not correct to add the voltage drops, it is not correct to add the impedances across which they occur, because the impedances are proportional to the voltage drops. In short, the resultant impedance of a resistor and capacitor in series is not obtainable by adding the individual impedances directly. Due to the phase shift, they must be added vectorially. The formula already given adds them vectorially. Let us substitute numerical values in the formula:

$$Z = \sqrt{(125)^2 + (318)^2} = \sqrt{15{,}625 + 101{,}124}$$

$$= \sqrt{116{,}749} = 342 \text{ k-ohms (approximately)}$$

This differs considerably from 443 k-ohms which we get by adding directly. By simple addition, the impedance between point *E* and ground comes out 101 k-ohms higher than the true value – 342 k-ohms. This error could lead us to believe that the bass signal taken off the divider at point *T* had a higher level than its true level. We would not be getting as much bass boost as we thought.

Resistor and Capacitor in Parallel. Although both reactance and resistance are expressed in ohms, the impedance of a resistor and capacitor in parallel cannot be found by the formula that gives the value of two resistors in parallel. A formula must be used which takes into account the fact that current through a capacitor is out of phase with voltage across a capacitor, whereas current through a resistor is in phase with voltage across the resistor. The correct formula for a resistor and capacitor in parallel is:

$$Z = \frac{R \times X_c}{\sqrt{R^2 + X_c^2}}$$

Let us use the formula to find the impedance of 0.01-μf, in parallel with 125 k-ohms, at 50 cps:

$$Z = \frac{125 \times 318}{\sqrt{(125)^2 + (318)^2}} = \frac{39{,}750}{\sqrt{15{,}625 + 101{,}124}}$$

$$= \frac{39{,}750}{\sqrt{116{,}749}} = \frac{39{,}750}{341.7} = 116 \text{ k-ohms.}$$

Where the reactance of the capacitor is very large compared to the resistor (ten or more times the ohmage of the resistor), no calculation is necessary. The impedance of the combination will be so close to the ohmage of the resistor that it may be considered as identical, for practical purposes. Where the reactance is very small (one-tenth the ohmage of the resistor, or less), the impedance of the combination may be considered as equal to the reactance of the capacitor. (In each case, the impedance is approximately equal to the smaller of the two ohmages.)